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An improvement on the management of biomass removal from vegetated channels and the methods used in runoff research

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An improvement on the management of biomass removal from vegetated channels and the methods used in runoff research

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CHAPTER 1. GENERAL INTRODUCTION

Soil erosion is the detachment, transportation, and subsequent deposition of soil particles (Lal 1998). Soil erosion is one of the most important mechanisms for movement of sediment within a watershed. Eroded sediment is often enriched in chemicals compared to the soil from which it originated because chemicals are associated with clay and silt, particles that are preferentially eroded due to their smaller size (Jacinthe et al. 2004). The selective nature of soil erosion can cause textural changes in coarse textured soils, making them even coarser (Young 1980; Walling and Moorehead 1989;).

The deposition of eroded sediment can cause a number of environmental problems. Sediment carries pollutants such as fertilizers, pesticides, and hydrocarbons and deposits them with the sediment at locations within or even outside of the source watershed (Jacinthe et al. 2004). Water clarity is reduced when sediment is suspended in water bodies, causing decreased light penetration. This inhibits the growth of some aquatic vegetation. Added sediment to rivers and streams alters natural streambank and channel dynamics, which can enhance stream bank and channel erosion (Lane 1955). Excessive sediment deposition in reservoirs can decrease the volume of reservoir storage (Fangmeier et al. 2006).

Problems associated with soil erosion and sediment deposition have led to subsidized programs and practices to combat soil erosion. Conservation tillage and no tillage are practiced on highly erodible soils to decrease detachment and transportation of soil particles (Langdale et al. 1979). Fiber mats and straw are applied to construction sites to minimize sediment export to storm water drains (Kaufman 2000). Conservation practices, such as grassed waterways and vegetated filter strips, are used in rural watersheds to capture sediment and runoff, reduce and prevent gully erosion, and minimize sediment export from watersheds (Natural Resources Conservation Service 2003, 2009).

Vegetative filter strips and grassed waterways are installed widely in the Corn Belt to minimize sediment export to rivers and streams (United States Department of Agriculture [USDA] 2008). Vegetative filter strips intercept runoff and cause sediment deposition before the runoff enters streams. Grassed waterways provide a stable conveyance of runoff from fields to prevent gully erosion. These conservation practices experience runoff from a wide variety of storms with different durations and intensities. Grassed waterways are designed to convey runoff occurring from a 10-year 24-hour storm (Natural Resources Conservation Service 2003). However, they often experience storms of lesser durations and intensities.

While it is widely accepted that grassed waterways and vegetated filter strips improve or maintain water quality, reduce erosion, and provide wildlife habitat, farmers often fail to recognize their environmental value. Farmers do receive some payment for installing conservation practices because grassed waterways and vegetative filter strips are included in the Conservation Reserve Program (CRP) (USDA 2008). The installation of conservation practices takes land, which was previously farmed, out of commodity crop production. When commodity values are high, it is more profitable to farm the land than to receive a rental payment from the CRP. Grassed waterways can make the land more difficult to farm for some farmers because grassed waterways break up straight rows, which can reduce the efficiency of the farm operation (Stevenson, personal communication, Wilson, personal communication).

It is the goal of the United States to replace by 2030 30% of the U.S. fossil fuel used in its small duty fleet with biofuels. Perlack et al. (2005) found that to reach the goal, biomass removal would have to be conducted on acres enrolled in the CRP. There are several conservation practices and programs within the CRP that result in planting perennial grasses, such as grassed waterways, riparian buffer strips, vegetated filter strips, and land in the Grassland Reserve Program (USDA 2008). These conservation practices and programs are implemented throughout the country on different landscapes. If biomass removal and sales is practiced on CRP land and the conservation practices associated with the CRP land maintain their primary function, an additional economic incentive would be present that would encourage the use of these perennial grass-based conservation practices.

If biomass removal from land in the CRP is conducted, the intended function of the CRP land has the potential to be compromised. If the intended function is compromised, it would be useful to know to what extent it has been compromised. Grassed waterways and vegetated filter strips are installed throughout the Corn Belt, and soils vary widely across this region. Typical storms vary widely in duration and intensity on land areas serviced by grassed waterways and vegetated filter strips in the Corn Belt. Experiments that use many different storm durations, rainfall intensities, soil types, and slopes need to be conducted to fully understand the effect of biomass removal on sedimentation, sheet erosion, and gully erosion from land in conservation practices. As more studies are conducted on the effects of biomass removal, the scientific community will gain a better understanding of how biomass removal affects conservation practice functions.

Grassed waterways are a conservation practice in the CRP installed to stably convey runoff from crop fields to streams. Sedimentation is not desirable in grassed waterways because it reduces their effectiveness. However, studies have shown that watersheds with grassed waterways have much less sediment export than do watersheds without grassed waterways (Fiener and Aurswald 2003a, 2003b). This would indicate that sedimentation, while not desirable, does occur in grassed waterways, or that soil from this channel conducting water runoff is being eroded at a rapid rate in the absence of grassed waterways. Understanding the dynamics of grass waterway versus no waterway and/or dynamics of grass waterway alternatives could lead to improved waterway design and even additional uses for the waterway such as biomass removal as a biofuel feedstock.

The management of perennial grass based conservation practices, such as vegetated filter strips and waterways, is based on studies conducted on small-plot runoff experiments (Dillaha et al. 1989; Magette et al. 1989; Lee et al. 1999; Arora et al. 2003). A widely used study method in the previously cited studies involves applying water mixed with sediment, and in some cases simulated rainfall, on small plots (<30 m^2) and collecting samples of the water/sediment mix applied and that which runs off; treatment effects are then determined by the difference in runoff volume versus volume introduced and sediment introduced versus that exiting the plot.

A method that could determine the proportion of introduced plot-derived sediment would be useful in small-plot experiments for several reasons. The results obtained from such experiments would likely influence the best management practices used in the field. Different grass species, cutting heights, storm durations, and biomass removal could all influence sediment retention and transport through plots and even impact sediment obtained from the plot itself. Sediment source “fingerprinting” has been conducted on large-scale (>20 ha) watershed studies with more than three sediment sources (Peart and Walling 1986; Walling and Moorehead 1989; Russell et al. 2001). It would stand to reason that similar methods could be applied to small-plot runoff experiments, although the goals of the plot experiments and the watershed studies may differ.

Objectives and Organization of Dissertation

The objectives of this dissertation are:

- To determine the effects of biomass removal from vegetated channels planted to different grasses on runoff and sediment export during 5 year return period 15 minute storms and
- To develop a method that is able to differentiate between introduced and plot-derived sediment in the runoff generated from small-plot runoff experiments.

These objectives were accomplished in studies described in Chapters 2 and 3 of this dissertation. These chapters are formatted as peer-reviewed journal articles that have been published and accepted in the *Journal of Biomass and Bioenergy* and the *Journal of the Soil and Water Conservation Society*, respectively.

Chapter 2 is entitled "Perennial Grass Management Impacts on Runoff and Sediment Export from Vegetated Channels in Pulse Flow Runoff Events." Chapter 3 is entitled "A Method to Adapt Watershed-Scale Sediment Fingerprinting Techniques to Small-Plot Runoff Experiments." Chapter 4 serves as a conclusion for this dissertation.

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CHAPTER 2

PERENNIAL GRASS MANAGEMENT IMPACTS ON RUNOFF AND SEDIMENT EXPORT FROM VEGETATED CHANNELS IN PULSE FLOW RUNOFF EVENTS

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A paper in press in the *Journal of Biomass and Bioenergy*

Abstract

The goal of the United States Congress is to replace 30% of United States petroleum with biofuels by 2030. If this goal will be accomplished, it is estimated that 25-50% of the land enrolled in the Conservation Reserve Program (CRP) will have its biomass removed. However, the purpose of many conservation practices enrolled in CRP is to improve or maintain water quality and not to serve as a source of biomass. This study was conducted to determine if biomass removal has an effect on runoff and sediment export from vegetated channels during low intensity storms that occur frequently. In June 2006, 24 channels were created that measured 2 m x 10 m. The treatments of grass species (big bluestem, corn, smooth bromegrass, and switchgrass) and biomass removal (removed, not removed) were applied to the channels in a split plot arrangement. Three times in 2007 and 3 more times in 2008, a 787 L load of water with suspended sediment was drained on the head and sides of each experimental unit and the entire load of water that ran off was collected, weighed, and sampled for sediment concentration. Biomass removal increased runoff and sediment by an average of 15% over the two years of the study. The channels planted to perennial C4 grasses were most effective at reducing runoff and sediment export, while the corn was consistently the least effective at reducing runoff and sediment export.

1. Introduction

Biofuels represent one of the most promising sources of renewable energy being discussed today [1]. The vision of the Biomass Research and Development Technical Advisory Committee, established by Congress, is to replace 30% of United States (US) petroleum with biofuels by 2030 [2]. It is estimated that it will take approximately 907 Mt of biomass annually to meet the goal of Congress [2].

There are many possible sources of biomass that can be removed from both forested and agricultural lands [2]. Under current management practices, the potential amount of biomass available to feed biorefineries is approximately 176 Mt y^{-1} [2]. With increased yields, improved technologies, and biomass removal from half of the land in the Conservation Reserve Program (CRP) it is estimated that approximately 453 Mt of dry biomass would be available per year. However, under the previous circumstances, combined with a land use change on 202,000 km^2 from row crop production to perennial grasses, agriculture could supply approximately 635 Mt. Those 635 Mt from agriculture, combined with the 334 Mt from forestland and CRP land, would meet the 907 Mt goal [2].

Soil erosion is defined as the detachment and movement of soil or rock by water, wind, ice, or gravity [3]. Soil erosion is a problem because it removes the most reactive components, leaving behind less productive land. The movement of reactive components, i.e., largely clay and organic matter, is a mechanism for carrying many pollutants into water bodies [4]. Tillage practices that leave residue on the soil surface, such as no till and strip till, are effective at reducing particle detachment relative to conventional tillage systems [5]. When reduced tillage does not reduce soil erosion enough or when it is not practical, conservation practices are put in place to keep eroded sediment from waterways. Two conservation practices in the CRP planted with perennial grasses are grassed waterways and vegetated filter strips. In 2007, the USDA reported that there were 2500 km^2 enrolled in these two conservation practices in the Corn Belt of the US (Ohio, Indiana, Illinois, and Iowa) [6]. However, the harvesting of biomass from land enrolled in CRP is heavily restricted [7]. The Natural Resource Conservation Service (NRCS) Conservation Practice Standard states that the intended purpose of these conservation practices (vegetative filter strips and grassed waterways) is to improve or maintain water quality, not to serve as a feedstock for future biorefineries [8 9]. If biomass removal from these conservation practices does not compromise water quality, multiple benefits may be realized from these perennial grass-based conservation practices. Periodic biomass removal has been recommended for filter strips because it would help to maintain low soil P levels [10].

Vegetated filters and grass waterways traditionally have been constructed to meet water quality and soil conservation goals. Water flows through those conservation practices either as sheet flow or channelized flow. Channelized flow intentionally dominates in grassed waterways [8]. Channelized flow is not preferred in vegetative filter strips, but it is often observed and recognized as a problem because vegetative filter strips are designed to control sheet flow [10 11].

Depending upon the type of storm and soil moisture content, the duration of a given runoff event could be on a scale of minutes, hours, or days [12 13]. For instance, if the soil moisture content is very high and an intense, long duration rainstorm occurs, most of that rainfall would run off because the soil would have a small capacity to allow the rain to infiltrate. However, if the soil moisture content is low and the storm is not intense and of short duration, the soil would have a much greater capacity to allow the rain to infiltrate and not runoff.

Conservation practices planted to different grass species have been found to have different runoff and sediment export masses when runoff mixed with sediment is applied to them. One study conducted in Iowa, USA found that filter strips planted to switchgrass (*Panicum virgatum*) removed approximately 10% more sediment than did filter strips planted to smooth bromegrass (*Bromus inermis*) during 1-hour long combined rainfall-run on events [14]. However, in another experiment that used similar methods, no differences were observed in runoff and sediment mass between filter strips planted to different grass species [15]. In a study that measured the effectiveness of five different perennial grass species filter strips at reducing runoff and sediment loss from cotton fields, no difference between four perennial C4 grasses and one perennial C3 grass was found [16]. The NRCS allows a wide variety of grasses to be planted in grassed waterways and vegetative filter strips [17 18]. Should biomass harvest be allowed, or simply be practiced by farmers independent of CRP, removal may affect runoff differently from conservation practices planted to different grasses.

Biomass must be harvested from land in the CRP to meet future biomass demands; this potentially includes biomass from grassed waterways and vegetated filter strips [2]. While those conservation practices could serve as a source of biomass, their intended function of water quality improvement should not be sacrificed. If biomass removal from conservation practices does not sacrifice water quality, they could potentially serve multiple benefits to the environment, farmer, and cellulosic biofuel industry. Potential economic return for the biomass harvested from conservation practices may increase the adoption of these conservation practices. Studies need to be done to determine if it is feasible to remove biomass from land in the CRP and maintain the intended function of the conservation practices. A simulated rainfall study was conducted in North Dakota, USA to determine the effects of grazing and haying (biomass removal) on runoff and erosion from former CRP fields [19]. They conducted two 24-hour simulated rainfalls (69 mm h^{-1}, 50 year return interval) on undisturbed CRP land and on CRP land that had the biomass removed annually [19]. Runoff did not occur in either of the runoff simulations on the undisturbed CRP and 42% of the simulated rainfall ran off of the hayed plots.

Runoff flows through perennial grass conservation practices either as sheet or channelized flow. Depending on the type of storm, the runoff event could last for minutes, hours, or days. The objective of this study was to determine if biomass removal affects runoff and sediment export from vegetated channels during 15 minute storms that have a 5 year return period on an area 20 times as large as the channels. We hypothesized that vegetated channels that have biomass removed would export more runoff and sediment than would vegetated channels that do not have their biomass removed.

2. Materials and Methods

2.1 Site Description

This experiment was conducted on the Woodrow Wilson farm, approximately 8 km south of Niota, IL, USA (40^{o} 35\` N, 91$^{o}$ 20\` W), beginning the summer of 2006. The soil on the research site was a Seaton silt (fine-silty, mixed, superactive, mesic Typic Hapludalfs) and the field had a 3% slope. This field has been planted to perennial grasses since 2004 because it was enrolled in the CRP. From approximately 1944 to 2004 the field was in corn (*Zea mays L.)*, soybean *(Glycine max L. Merr)*, and wheat (*Triticum aestivium L.)*

production. In 2006, when the experiment began, the field had a pH of 6.5 and organic C content of 1.1% at the 0-6 cm soil depth and its texture was 11% sand, 88% silt, and 1% clay.

2.2 Experimental Unit Construction

In May of 2006, the study site was sprayed with Glyphosate to kill all of the grass in the area of the study site. After the grass died, the dead grass was incorporated into the soil using a disc-harrow. The soil was then tilled to the 15cm soil depth using a power take-off driven tiller, which produced a uniform and finely tilled seed bed. The experimental units (n=24) were then established. Each experimental unit was 2m wide x 10m long.

The next step in the experimental unit construction was to shape the channels. A trapezoidal shaped template was formed from 0.9 cm wide plywood to have a 30 cm flat bottom and sides that had a slope of 12.7%. This slope would be comparable to the slope of the sides of a grassed waterway [8]. This template was pulled through each plot and soil was raked away from the template or backfilled underneath the template as needed so that the bottom of the experimental unit had the same shape as the bottom of the template. After all experimental units were shaped; they were rolled with a lawn roller to create a firm seedbed. The pressure exerted on the soil surface was a uniform 158 kPa. This resulted in a 2 m wide channel with a 0.3 m horizontal base and 12.7% side slopes (Figure 1).

2.3 Experimental Design and Treatment Application

The experimental design used in this study was a split-plot design with three replications. The whole plot treatment was grass species and biomass removal was the split treatment. Big bluestem (*Andropogdon gerarrdi)* 'Kaw,' switchgrass 'Blackwell,' and smooth bromegrass 'Lincoln' were planted on 12 June 2006 at the rates of 7, 10, and 10 kg ha^{-1}, respectively. The stem density of the grass stands was measured in February 2009 by counting the number of stems in two randomly placed $0.1m^2$ quadrants (Table 1). The corn plots were left fallow in 2006 and corn was planted on 7 May 2007 and 8 June 2008. The corn was planted in rows perpendicular to water flow, the rows were spaced 0.9 meters apart, and the seeds were spaced approximately 0.1 m apart. Broadleaf weeds were controlled with 2, 4-D in April and June of 2007 and 2008 in the grass plots and weeds were controlled with glyphosate in April and June of 2007 and 2008 in the corn plots.

In October of 2006 and 2007, all of the plots (biomass removed and not removed) were mowed with a gas-powered, hand-held weed clipper at a height of 10 cm. Then the aboveground biomass was removed from the plots that received the biomass removal treatment by raking the biomass with lawn rakes and then taking it off-site. Prior to mowing the plots, all of the aboveground biomass (live and dead) was taken from three randomly placed 0.1 m^2 quadrants in each plot that received the biomass removal treatment. These samples were placed in paper bags, dried at 65^oC, and weighed to estimate the amount of biomass removed from each plot.

2.4 Field Methodology

In June, August, and October of 2007 and in April, June, and August of 2008, a 787 L load of water was applied to each plot at a rate of 80 L min^{-1}. The volume of runoff applied to each plot was approximately the volume of runoff that would be produced by a 15 minute storm with a 5 year return period on an area 20 times larger than the plots. This return period was estimated using the SCS curve number method [12]. Sediment was mixed into each load of water to produce a sediment concentration of 10 g L^{-1}. The sediment was obtained by collecting soil approximately 3 km from the study site at the 0-5 cm soil depth and then the soil was air dried. The collected soil was in the same mapping unit as was the soil at the study site (274B). After the soil was dry it was passed through an 8mm sieve and hand-mixed to homogenize it. Prior to and during the application of the water, the water with sediment mixed in was constantly stirred by a person with a spade-type shovel. The water mixed with sediment was intermittently sampled as it was drained on each plot to determine the amount of sediment that was applied to each plot.

The water with sediment mixed in was pumped from the tank using an ACE 150 Pro Series (maximum pressure = 760 kPa, maximum flow = 378 L min^{-1}) power take off driven pump on a John Deere Model 7410 tractor with the revolutions per minute of the tractor set at 1200, resulting in an output of 80 L min^{-1} (ACE Pump Corporation, Memphis, TN). The pump had 3.2 cm suction and discharge ports. The water with sediment was pumped into an application mechanism constructed with 3.2 cm diameter polyvinyl chloride pipe (Figure 1). The application mechanism was 2 m wide at the head of the plot and extended 6.5 m down both sides of the plot. Every 15 cm, along the whole application mechanism, a 0.6 cm hole was drilled from which water flowed onto the plot.

The entire load of water that ran off each plot was collected and weighed. A 1 L sample was intermittently collected from the application mechanism as the water was being pumped on the plot and as water ran off the plot. Sediment concentration in the water was determined by passing 50 ml of the sample through an oven-dried 0.45 micron filter. The soiled filter was then oven dried to determine the mass of sediment in 50 ml of sample. From that data sediment concentration was calculated.

Soil bulk density was measured in September 2008 at the 0-15cm soil depth by sampling 3 randomly located positions within each experimental unit, using a 1.65 cm diameter soil probe. The cores were dried for 24 hours at 105^{o}C, and then weighed. The mass of the dried soil cores was divided by the total volume of the three cores to determine bulk density. Soil moisture was monitored during 2008 at the 0-30 cm soil depth using a MP-17 TDR (Environmental Sensors Inc, Sidney, British Columbia, Canada). One set of probes was installed in the center of each plot and the probes were sampled approximately every 10 days from May 12 to August 8.

2.5 Statistical Analysis

The experimental design used in this study was a split-plot design with three replications. The data were analyzed by year because corn planting was delayed in 2008 and only present in one of the three runs of the experiment, while it was present in every run of the experiment in 2007. The data were first analyzed as a split-plot in time where grass species, biomass removal, and month were fixed factors and replication was treated as a random factor. If there was no interaction between month and grass species or month and biomass removal, the masses of runoff and sediment were added together for each plot and the data were analyzed as a split-plot with grass species being the whole plot and biomass removal being the split plot. Means were separated in the grass species using contrasts statements and means were separated in the biomass removal treatments by calculating a least significant difference (LSD). All of the ANOVA, contrast statements, and LSD calculations were done using PROC GLM (SAS Institute version 9.1, Cary, NC). When an interaction occurred, t-tests were used to separate means between treatments and the calculations were done using Microsoft Excel (Microsoft Corp, Redmond, WA).

3. Results

The results from the split-plot in time analysis indicated no interactions existed between month and grass species or month and biomass removal (P values between 0.22 and

0.93). Because there were no interactions, the data are presented as the total amount of runoff and sediment collected from each treatment for all three experimental runs in each year.

In the analysis of the 2007 runoff data, there was a significant interaction between grass species and biomass removal (Table 2). The vegetated channels that were planted in switchgrass with biomass removal had 22% more runoff (P=.037) than did the channels planted to switchgrass that did not have their biomass removed (Figure 2). However, this was the only significant interaction between grass species and biomass removal for all of the parameters measured (P values 0.40-0.79).

3.1 Grass Stand Density

Grass stems were counted in March of 2009 and separated into planted species (target) and non-planted species (non-target). The plots planted to smooth bromegrass were a monoculture of smooth bromegrass (Table 1). In the plots planted to switchgrass, 52% of the stems present were switchgrass. In the plots planted to big bluestem, 12% of the stems present were big bluestem stems. The non-target species plants in the vegetated channels planted to switchgrass and big bluestem were primarily foxtail (*Sertaria spp.*).

3.2 Grass Species

In 2007, sediment concentration in the runoff was not affected by grass species (P=0.31). However, runoff and sediment export were significantly different between the vegetated channels planted to different grass species (P=0.03 and 0.04, respectively). The vegetated channels planted to perennial C4 grasses had 75% as much runoff and 79% as much sediment export compared to the average of the vegetated channels planted to smooth bromegrass and corn (Table 3).

Grass species had a significant effect on both runoff and sediment export in 2008 (P values = 0.006 and 0.06, respectively). The perennial C4 grasses and smooth brome grass vegetated channels had an average of 75% as much runoff and 57% as much sediment export compared to the vegetated channels planted in corn (Table 3). Grass species had no effect on sediment concentration (P=0.60)

3.3 Biomass Removal

Removing aboveground biomass from the vegetated channels resulted in a significant increase in runoff and sediment export in 2007 (P=0.03 and 0.10, respectively). The vegetated channels that had their aboveground biomass removed had 12% more runoff and 17% more sediment export than did the vegetated channels that did not have their biomass removed (Table 4). Biomass removal had no effect on runoff sediment concentration in 2007 (P=0.43).

Biomass removal from the vegetated channels resulted in a significant increase in runoff in 2008 (P=0.08). The vegetated channels with aboveground biomass removed had13% more sediment export than did the vegetated channels that did not have their biomass removed (Table 4). However, biomass removal had no effect on sediment concentration in the runoff or sediment export in 2008.

3.4 Soil Moisture and Bulk Density

Surface-soil (0-15cm) bulk density was 0.1 g cm^{-3} greater in the vegetated channels planted in corn than in the vegetated channels planted in smooth bromegrass and perennial C4 grasses (Table 5). Soil moisture was measured throughout the 2008 experiment year and there was no day that the treatments had an effect on soil moisture (Fig 3).

3.5 Mass of Biomass Removed

No significant differences were observed in the amount of aboveground biomass removed from the vegetated channels planted to different grass treatments in 2006 (Table 6). In 2007, the vegetated channels planted to perennial C4 grasses and corn had an average of 32% more biomass removed compared to the vegetated channels planted with smooth bromegrass.

4. Discussion

The removal of biomass from land in the CRP will be required to meet the biomass needs of the USA by 2030 if we are to meet the renewable fuel goals set by Congress. However, the intended purpose of many conservation practices enrolled in the CRP program is to conserve soil resources and improve or maintain water quality, not to serve as a source of biomass. If the intended purpose of the conservation practice is not sacrificed while having biomass removed, multiple benefits could be realized from those conservation practices.

In the third year after the construction of the vegetated channels, switchgrass stems comprised 52% of the stems in the channels planted to switchgrass and big bluestem stems accounted for 12% of the stems in the channels planted to big bluestem (Table 1). The total number of stems per square meter is similar to previously reported values [14]. The relatively low establishment numbers of the perennial C4 grasses was most likely due to poor weed control in the year the grasses were planted [20]. While the establishment of the perennial C4 grasses in the vegetated channels used in this study was not optimal, this establishment may represent that likely to be observed in similar vegetated channels planted to perennial C4 grasses. These grasses are difficult to establish due to seed dormancy, weed pressure, and moisture and sunlight availability [21 22]. The establishment of switchgrass and big bluestem is more successful when corn is used as a companion crop and atrazine [6-chloro-N-ethyl-N-(1-methylethyl)-1, 3, 5-triazine-2, 4-diamine], which is labeled for corn, is applied to reduce weed pressure when the grasses are planted [20].

The analysis of the data as a split plot in time indicated that there was no month x biomass removal or month x grass species interactions. This can be interpreted as there was no effect of seasonality on the runoff or sediment export from the vegetated channels under the experimental procedures used. There was one interaction between grass species and biomass removal and it was for runoff in 2007. Removing aboveground biomass did increase runoff in the vegetated channels planted to switchgrass. However, the vegetated channels planted to switchgrass with the biomass removed had less runoff than did the vegetated channels planted to smooth bromegrass and corn that had no aboveground biomass removed. Switchgrass is normally mowed during the establishment years, whether or not biomass is removed, for the purposes of weed control.

Immediately after the vegetated channels were mowed in October, the biomass formed a mat on top of the uncut stubble. This mat could protect the soil in the vegetated channels from rainfall impact, but would not interact with shallow runoff. During the months of December through February the vegetated channels were covered with 15-30 cm of snow. After the snow melted, the biomass that was left in the channels was in direct contact with the soil surface. The mass of the snow combined with its melting seemed to cause the biomass to fall onto the soil surface allowing the biomass to interact with runoff when it was applied. The vegetated channels that had biomass removed did not have mowed biomass in contact with the soil surface, only the stubble from the cut grass remained.

Aboveground biomass removal generally increased runoff and sediment export from the vegetated channels. However, increases in runoff and sediment export were relatively small (increases between 13-17%). Similar results have been found with regards to biomass removal, in that the plots with biomass removed had more runoff and sediment export [19]. However, the differences in runoff and sediment export from plots with and without biomass removed were much more dramatic than in this study. This could be due to the fact that the study used a 24 hour storm with 50 year return interval and this study used a 15 minute storm with a 5 year return period [19]. While the storm used in this study is less intense, storms representing this intensity and duration occur more frequently and their impacts on runoff and soil erosion should be recognized. The study attributed differences to the fact that there was less soil surface roughness in plots with biomass removed.

The timing of biomass removal has the potential to affect runoff and sediment exported from vegetated channels. Switchgrass grown for biomass typically yields the most with only one cutting and when harvest is conducted after the first killing frost [23]. The grasses then begin to grow when the soil temperature reaches 16°C [23 24]. This means that grasses grown for biofuels at the study site would provide new cover for the soil from late spring though late fall or early winter. However, there would be stubble and some unharvested biomass left over from the previous year's biomass harvest because the harvest would not be 100% efficient in removing all of the aboveground biomass [19]. The time period of early winter through late spring exhibits conditions for which soil would be most susceptible to erosion under a biomass for bioenergy system. This would be a concern because approximately one third of annual precipitation in this region falls during that time period and snowmelt increases the volume of runoff that would flow through vegetated channels (Fig. 4) [25]. However, the switchgrass grown for biomass would provide cover for the soil for approximately two thirds of the precipitation that the study site would receive.

The grass species planted in the vegetated channels affected the amount of runoff and sediment exported from them. The general trend over the two years of this study was that the vegetated channels planted to perennial C4 grasses were most effective at reducing runoff and sediment export, smooth bromegrass was sometimes as effective as the perennial C4 grasses, and corn was the least effective. This result is similar to previous research conducted on the effects of grass species on runoff from grass filter strips [14 16 26]. Some research suggests that this difference occurs because the stems of the perennial C4 grasses are much stiffer than are the stems of cool-season C3 grasses and the stiffer stems can provide more resistance to the flow of surface runoff [27]. While the establishment of perennial C4 grasses can be difficult, as observed in this study, establishing stands of perennial C4 grasses were just as or more effective at reducing runoff and sediment export when compared to the widely recommended smooth bromegrass [18 28].

If perennial C4 grasses are going to be used to feed biorefineries, they must first be established on CRP land or other farmland. Perennial C4 grasses can be difficult to establish and this establishment phase could be the most critical from a soil loss perspective. As previously noted, the establishment of the perennial C4 grasses was moderate at best three years after planting. The smooth bromegrass was a well-established monoculture three years after planting. While the perennial C4 grasses were not fully established like the smooth bromegrass, the vegetated channels with perennial C4 grasses were just as, or more, effective at reducing runoff and sediment export. This suggests that the non-target species in the vegetated channels are effective at reducing runoff and sediment export while the perennial

C4 grasses are establishing. This would mean that vegetated channels planted to perennial C4 grasses, while difficult to establish, are not more susceptible to increased runoff and soil loss than is a quickly establishing grass, smooth bromegrass.

Biomass will have to be removed from land enrolled in the CRP program [2]. Many conservation practices in the CRP have vegetated channels in them (either intentionally or unintentionally) and the purpose of those conservation practices is to reduce channel erosion and improve or maintain water quality. The results from this study indicate that biomass removal increased runoff and sediment export from vegetated channels by an average of 15% during 15 minute, 5 year runoff events. If landowners were allowed to remove and sell biomass from conservation practices, a new benefit for installing conservation practices would arise. An economic incentive associated with conservation practice installation would have the potential to increase the amount of conservation practices installed and maintained within a watershed. An increase in the amount of conservation practices could offset the potential increase in runoff and sediment export related to biomass removal.

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Figure Captions

Figure 1. Cross section (A) and plane view (B) of the experimental units and the orientation of the application mechanism with respect to the plot.

Figure 2. Annual percent runoff reduction in 2007 comparing the effect of biomass removal within each grass species. The effect of biomass removal within each grass species was compared using a t-test and differences were assessed when $p<0.05$. Different letters above bars, within each grass species, indicate the annual percent runoff reductions are different at $p<0.05$.

Figure 3. Volumetric soil moisture at the 0-30 cm soil depth during the 2008 experimental year. * Indicates significant differences at $p<0.05$.

Figure 4. Mean monthly temperature and precipitation in central Illinois from 1971 to 2000.

Figure 1.

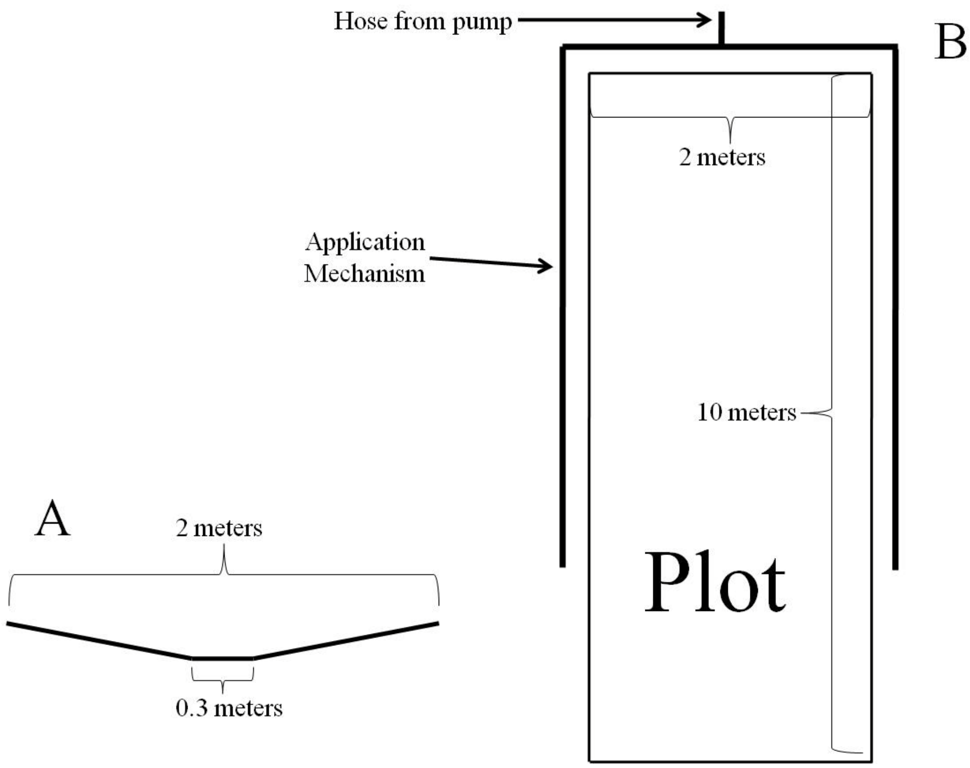
Hose from pump
B
2 meters
Application
Mechanism
10 meters
A
2 meters
Plot
0.3 meters

Figure 2.

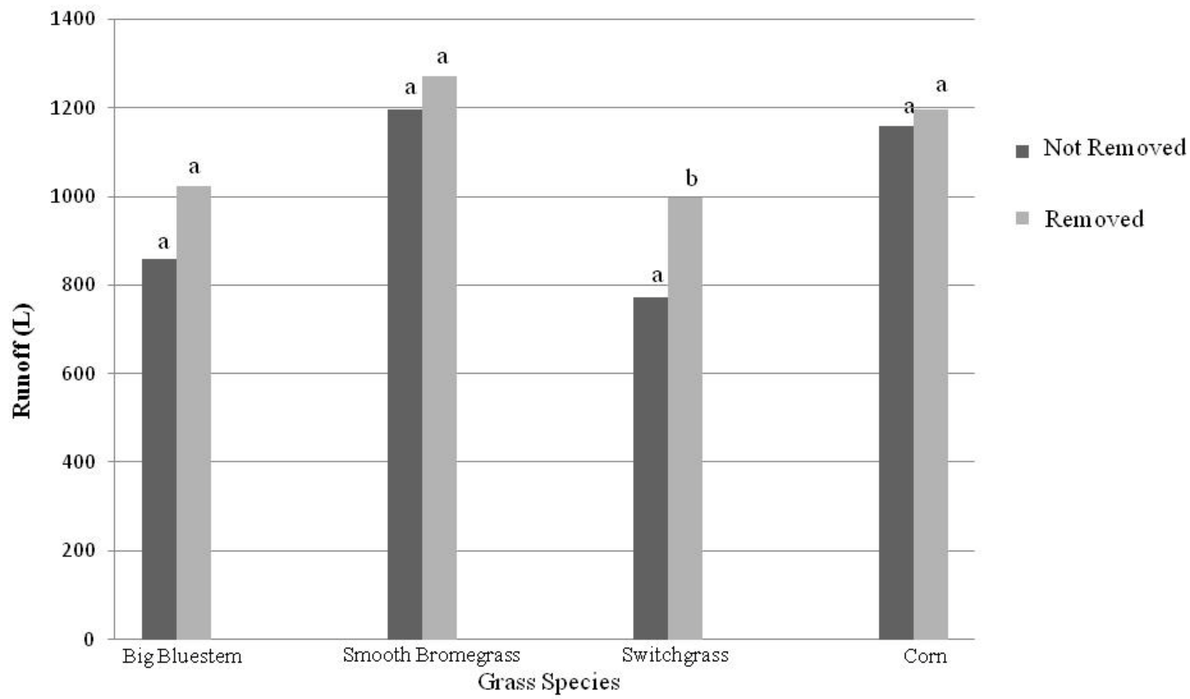
1400
1200
1000
800
600
400
200
0
Runoff (L)
a
a
a
a
a
b
a
a
Big Bluestem
Smooth Bromegrass
Switchgrass
Corn
Grass Species
Not Removed
Removed

Figure 3

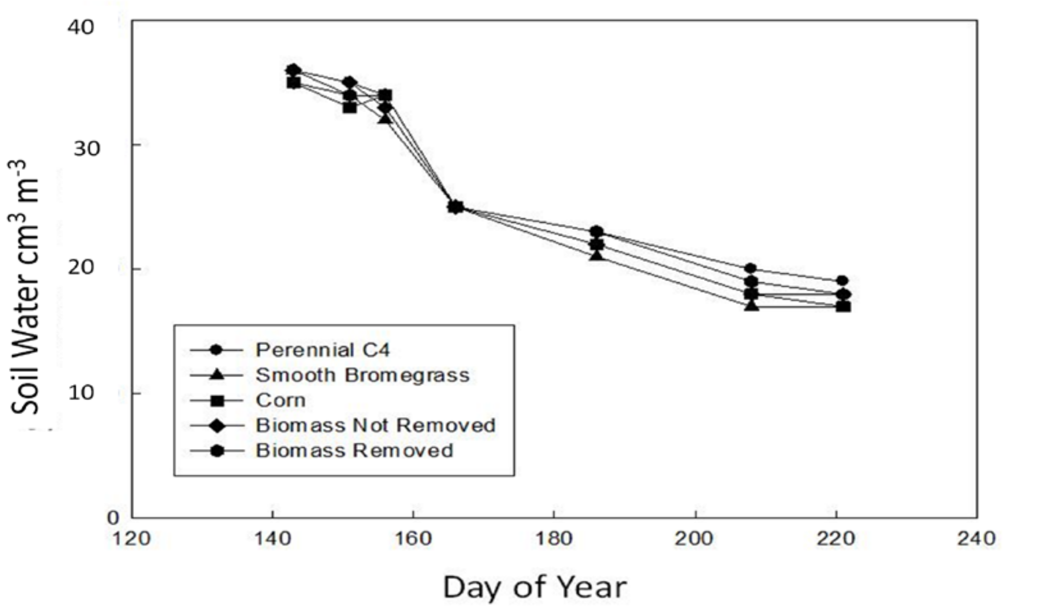
40
30
20
10
0
Soil Water cm3 m-3
120
140
160
180
200
220
240
Day of Year
Perennial C4
Smooth Bromegrass
Corn
Biomass Not Removed
Biomass Removed

Figure 4.

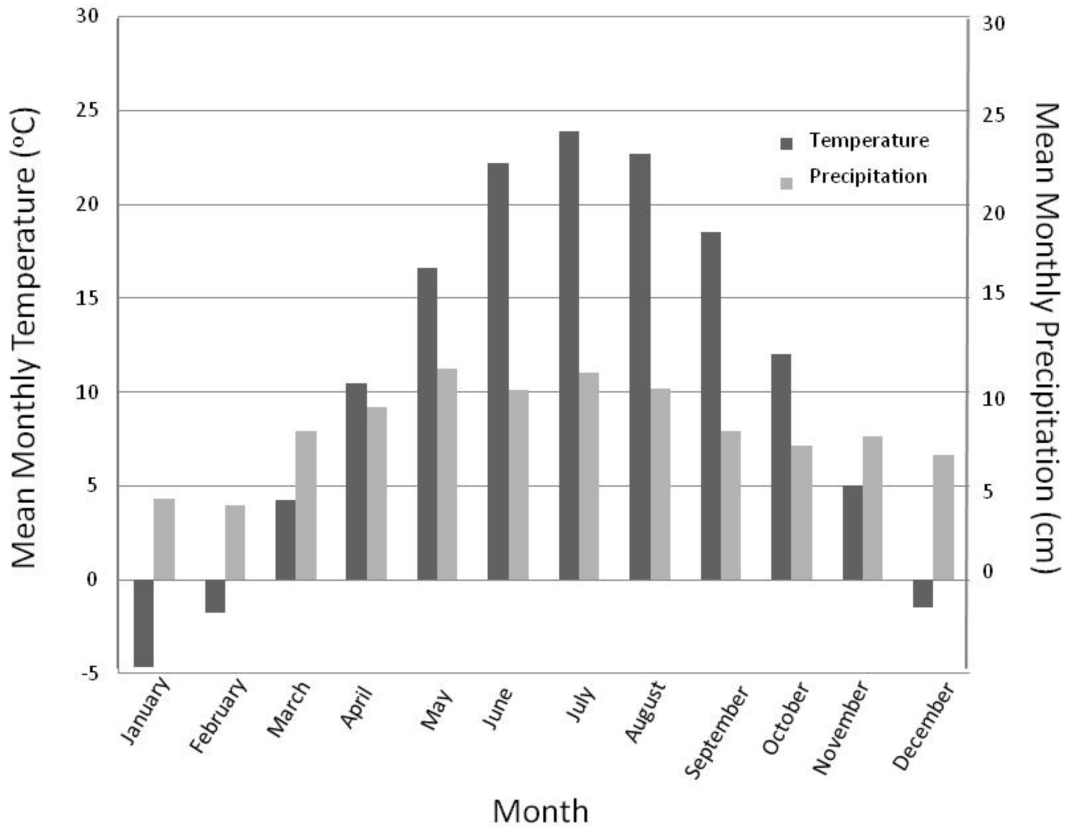
Mean Monthly Temperature (°C)
Mean Monthly Precipitation (cm)
Temperature
Precipitation
30
25
20
15
10
5
0
-5
January
February
March
April
May
June
July
August
September
October
November
December
Month

Table 1. Grass stems present in the experimental units based on target species (the species that was planted) and non-target species.

Grass Species	Stems of target species present (stems m^{-2})	Stems of non-target species present (stems m^{-2})
Big Bluestem	100 (49)*	703 (181)
Smooth Bromegrass	795 (46)	0
Switchgrass	357 (65)	325 (162)

*Number in parentheses is the standard deviation of the mean

Table 2. Analysis of variance table for runoff in 2007

Source	D.F.	Mean Square	F value	P value
Block	2	71231	41	<0.001
Grass	3	56337	33	0.07
Block x Grass	6	14273	8	<0.001
Biomass Removal	1	32264	18	<0.001
Grass x Biomass Removal	3	4159	2	0.08

Table 3. Grass species effects on runoff, sediment export from vegetated channels and sediment concentration in the runoff water in 2007 and 2008

Year	Grass	Runoff (L)	Sediment (g)	Sediment conc. (g L^{-1})
2007				
	Perennial C4	900a	615a	0.69a
	Smooth Bromegrass	1236b	873b	0.71a
	Corn	1179b	861b	0.73a
2008				
	Perennial C4	774a	1128a	1.7a
	Smooth Bromegrass	906a	1080a	1.2a
	Corn	1119b	1935b	1.7a

Values in the same year with different letters are significantly different at $P<0.05$

Table 4. Biomass removal effects on runoff and sediment export from vegetated channels in 2007 and 2008

Year	Biomass Removal	Runoff (L)	Sediment (g)	Sediment conc. (g L^{-1})
2007				
	Removed	1128A	816a	0.74a
	Not Removed	999B	672b	0.67a
2008				
	Removed	951a	1398a	1.46a
	Not Removed	831b	1236a	1.67a

Values in the same year with different uppercase letters are significantly different at $P<0.05$
Values in the same year with different lowercase letters and are significantly different at $P<0.10$

Table 5. Bulk density of the grass and biomass removal treatments measured at the 0-15 cm soil depth.

Treatment	Bulk Density (kg m^{-3})
Grass	
Perennial C4	1.6a
Smooth Bromegrass	1.6a
Corn	1.7b
Biomass Removal	
Removed	1.6a
Not Removed	1.6a

Values with different letters within each treatment are different at $p<0.05$

Table 6. The amount of biomass removed from the vegetated channels that received the biomass removal treatment.

Year	Grass	Biomass Removed (g m^{-2})
2006		
	Perennial C4	343a
	Smooth Bromegrass	388a
	Corn	453a
2007		
	Perennial C4	516a
	Smooth Bromegrass	159b
	Corn	466a

Values in the same year with different letters are significantly different at $P<0.05$

CHAPTER 3

A METHOD TO ADAPT WATERSHED-SCALE SEDIMENT FINGERPRINTING TECHNIQUES TO SMALL-PLOT RUNOFF EXPERIMENTS

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Abstract

Suspended sediment in rivers, lakes, and streams has been identified as a problem for several reasons. Watershed scale studies are often conducted to identify primary sediment sources utilizing scale appropriate soil fingerprinting methods. However, fingerprinting has not been attempted in small-plot runoff experiments to better understand sediment dynamics related to management practices. The objective of this study was to apply sediment fingerprinting techniques to small-plot runoff experiments to determine the relative contribution of the plot and applied sediment to sediment exported from small plots. Sediment-free water was applied to the head and sides of constructed vegetated channels in March and September of 2008. A 10 L sample of the runoff was collected, the water was evaporated from it, and the remaining sediment was ground and analyzed for total C. Water mixed with soil material obtained from a different part of the landscape and with a higher soil C content than that of the plot soil was applied to the head and sides of the vegetated channels, the mixture was sampled as it was applied, and the resulting runoff from the plot was sampled. These runoff samples were processed and analyzed for total C similarly to those collected when sediment-free water was introduced to the upper end of the plot. Based on differences in total C of the plot soil and the introduced soil material, a linear relationship was developed allowing the

sediment exiting the plot to be partitioned between that soil material introduced with the inflow and that soil coming from the plot bed. The sediment C content was entered into the linear equation to determine the percent plot-derived sediment in the runoff. When soil material mixed with water was introduced to the plots, on average 20.5 % of the sediment in runoff was derived from within the plot. The sediment trapping efficiency of the vegetated channels was very high (over 90%) and, accounting for percent plot-derived sediment, had little effect on sediment trapping efficiency.

Introduction

Suspended sediment in rivers, lakes, and streams has been identified as a problem for several reasons. Suspended sediment in aquatic ecosystems can be a problem because it decreases light penetration and is harmful to aquatic organisms (Cordone and Kelley 1961). Stream channel and bank properties can be altered with increases in suspended sediment concentration (Lane 1955). Several pollutants, including pesticides, heavy metals, and phosphorus, are delivered to aquatic ecosystems via suspended sediment (Fangmeier et al. 2006). Due to the problems that excessive suspended sediment can cause, several measures have been put in place to minimize sediment delivery to rivers, lakes, and streams. Conservation tillage and no till operations have been found to minimize sediment delivery from agricultural fields to waterways (Langdale et al. 1979). Fences and mats are often installed on construction sites, which are a significant source of suspended sediment in urban watersheds (Kaufman 2000). Conservation practices, such as grassed waterways and filter strips, are often installed in and around agricultural fields to minimize sediment delivery to water courses (Natural Resource Conservation Service 2003, 2009; United States Department of Agriculture 2008).

Identifying from where suspended sediment originates within a watershed is critical for addressing problems associated with suspended sediment in water bodies (Walling et al. 1993). Knowing the source of suspended sediment is beneficial as this allows efficient targeting of conservation practices. Understanding the source of sediment is also important in developing sediment budgets and sediment yield models (Walling et al. 1993). A common method in sediment source identification, often called sediment "fingerprinting," identifies one or several soil chemical parameters at the different sources and use mixing models to delineate the relative contribution of each source (Peart and Walling 1986; Walling et al. 1993; Kronvang et al. 1997). Different soil parameters used include: total C, total N, ^{137}Cs, ^{210}Pb, conductivity, magnetic properties, total P, and Mn (Peart and Walling 1986). Sediment fingerprinting has been conducted in several watershed-scale studies (Peart and Walling 1986; Walling et al. 1993; Kronvang et al. 1997). A challenge using this technique involves organic C enrichment of sediment in runoff relative to the soil from which the sediment originated (Truman et al. 2007). Also, sediment is often enriched in silt-sized particles and depleted in sand-sized particles relative to the soil from which the sediment originated (Young 1980; Walling and Moorehead 1989). These problems have been overcome in sediment fingerprinting studies by calculating organic C and particle size enrichment factors and multiplying observed values with the enrichment factor (Peart and Walling 1986).

While sediment fingerprinting has been conducted in watershed-scale studies, it has never been attempted in small-plot runoff experiments. Small-plot runoff experiments are often conducted to develop best soil conservation practices. Small-plot runoff experiments could involve simulating rainfall and/or applying runoff mixed with sediment to small plots, usually less than 100 m^2 (1070 ft^2), and measuring the water and sediment in the plot runoff water (Dillaha et al. 1989; Magette et al. 1989; Lee et al. 1999; Arora et al. 2003). A combination of rainfall and runoff were applied to riparian buffers planted to different species in central Iowa, and the buffers planted to switchgrass (*Panicum virgatum*) had a total of 10% less runoff than did the buffers planted to smooth bromegrass (Lee et al. 1999). Switchgrass is commonly more effective at minimizing runoff due in part to its rigid stem. These types of experiments offer controlled conditions to more accurately compare sediment movement dynamics for different treatments. For example, Dillaha and Inamdar (1996) conducted a literature review and determined that conservation practices, such as grass buffers, can be sediment sources or sinks, depending on buffer age and watershed management practices. The ability to know when a conservation practice becomes a source rather than a sink for pollutants would be useful to know because it could help improve design of the practice or could help identify when the lifespan of the conservation practice has been exceeded. It would also give scientists a better understanding of whether or not the conservation practice is losing effectiveness.

Small-plot runoff experiments often calculate the amount of sediment trapped in the conservation practice by subtracting the amount of sediment in the runoff from the amount that was applied (Lee et al. 1999). Sediment trapping efficiency is calculated by dividing the amount of sediment trapped by the amount of sediment applied. This calculation does not account for the possibility that some of the sediment in the runoff may have originated from within the plot. If some of the sediment in the runoff comes from within the plot, then the amount of the applied sediment actually trapped in the conservation practice would be greater than the current calculation identifies. This weakness in calculating trapping efficiency provides misleading results when discussing actual sediment trapping efficiencies of different conservation practices.

If sediment fingerprinting can be conducted in watershed-scale studies, it would stand to reason that the approach should work in small-plot runoff experiments (Walling et al. 1993). Both types of studies, watershed-scale and small-plot runoff, measure suspended sediment in runoff derived from multiple sources. However, sediment fingerprinting in small-plot runoff experiments is simpler than in watershed-scale studies and should allow for more rigorous evaluation of sediment sources. In small-plot sediment loss experiments there are only two sources of sediment: the applied sediment and the sediment that originated from within the plot. In watershed-scale studies there are many sources of sediment depending on the watershed including: stream bank, stream channel, agricultural fields, and urban areas. Watersheds receive storms with varying duration and intensity, leading to different runoff rates with different amounts of organic C and selective particle size enrichment in the runoff. During small-plot runoff experiments the runoff rate applied to the plots can be controlled.

The objectives of this study were to apply simplified watershed-scale sediment fingerprinting techniques to small-plot runoff experiments to determine the relative contribution of the plot and applied sediment to sediment exported from small plots and to determine the actual amount of applied sediment that was trapped. We hypothesized that by measuring the total C content of applied and plot sediment during small plot runoff experiments, then measuring the runoff sediment C content, the relative contribution of plot and applied sediment could be determined and that plots do contribute some sediment to runoff so plots are trapping more applied sediment than traditionally reported.

Materials and Methods

This study was part of a larger study that addressed the effects of biomass removal from vegetated channels planted to different grass species on runoff and sediment export (Wilson et al. 2010). The experiment was conducted on the Woodrow Wilson farm approximately 5 miles south of Niota, IL, USA (40^{o} 35\` N, $91^{o}$ 20\` W). The site had been in corn (*Zea mays L.)*, soybean *[Glycine max (L.) Merr]*, and wheat (*Triticum aestivium L.)* production from 1940–2004, then planted to perennial grass in 2005. The soil at the study site was a Seaton silt (fine-silty, mixed, superactive, mesic Typic Hapludalfs) with a 3% slope. When the experiment began in 2006 the field had a pH of 6.5, soil organic C content of 1.1%, and soil particle size distribution was 11% sand, 88% silt, and 1% clay. Measurements were made on soil samples collected from the 0-15 cm soil depth. Organic C was determined by dry combustion and texture was determined using a sieving and settling method developed by Kettler et al. (2001).

Twenty-four vegetated channels were constructed at the study site in June of 2006. The channels measured 2m x 10m (6.5 ft x 32.8 ft) with a 0.3m (1 ft) flat bottom and 12.7% sideslopes. They were constructed by dragging a template with a 0.3 m (1 ft) flat bottom and 12.7% sideslopes through loosely tilled soil. The width of the channels was then measured and channel edges were rolled with a lawn roller to establish a width of 2 m (6.5 ft). A cross section and aerial view of the vegetated channels can be seen in Figure 1. After the channels were formed they were rolled with a 1500 kg (3300 pound) lawn roller to create a firm seedbed. Big bluestem (*Andropognon gerardi)* 'Kaw,' switchgrass 'Blackwell,' and smooth bromegrass (*Bromus inermis*) 'Lincoln' were planted by broadcasting on 12 June 2006 at the rates of 7, 10, and 10 kg ha^{-1}(6.2, 9, and 9 pounds $acre^{-1}$), respectively. The vegetated channels to be planted to corn were left fallow in 2006, and corn was planted perpendicular to the direction of flow in 2007 and 2008 in rows spaced 0.9 m (2.9 ft) apart with a plant every 0.1 m (0.3 ft).

In March and September of 2008, sediment-free water was applied to the head and sides of 8 randomly selected vegetated channels using a runoff application device that measured 2 m x 6.5 m (6.5 ft x 21.4 ft) (Figure 1). The runoff application device had holes drilled every 0.15 m (0.5 ft) through which water flowed onto the vegetated channels. Water flowed onto each vegetated channel at a rate of 80 L min^{-1} (21 gallons min^{-1}) for sufficient time to generate 10 L (2 gallons) of runoff from the vegetated channels, and this runoff was collected in a 10 L bucket. Water from the runoff samples was evaporated, the sediment that remained was brushed from each bucket onto white paper, and any roots or plant litter was removed. The sediment samples were then mixed in a SPEX 8000M Mixer/Mill (SPEXcertiprep Group, Metuchen, NJ) for 4 minutes. This sediment sample represented sediment that originated from within the plot.

Approximately 500 kg of soil from the 0-5 cm (0-2 inch) soil depth was collected from an area with the same soil mapping unit (274B) within 2 miles of the study site. The soil was passed through an 8 mm sieve and air dried. Seven hundred eighty-seven L (208 gallons) of water mixed with 7 kg (15.4 pounds) of the soil was applied to the head and sides of the 8 randomly selected vegetated channels at a rate of 80 L min^{-1} (21 gallons min^{-1}) in April, June, and August of 2008 using the previously described runoff application device (Figure 1). The sediment in the water was constantly stirred with a spade to keep sediment suspended. The water was sampled as it ran on and ran off of each vegetated channel approximately every 30 seconds to fill a 1 L (0.26 gallon) Nalgene bottle. The water samples were then processed similarly to the water samples that were collected in March and September (described previously). The sediment in the water being applied to the plot represented sediment not originating from within the plot. The sediment in the collected runoff water sample represented sediment that was potentially a mix of the plot sediment and applied sediment.

All collected sediment samples were dried at 105°C (221°F) for 24 hours and analyzed for total C on a Thermo Finnigan Flash EA1112 (Thermo Scientific, Waltham, PA). Sediment texture was determined for the applied sediment, plot sediment, and runoff sediment for each of the 3 months on a composite sample from the 8 vegetated channels (Kettler et al. 2001). The percent sand, percent silt, and percent clay of the applied sediment and runoff sediment were compared using a t-test (n=3). The total C content of the sediment that originated from the plot and the applied sediment samples were plotted as a function of percent plot-derived sediment (0% or 100%), and a linear regression equation was calculated for this relationship. The total C content of sediment collected from the water that subsequently ran off the plot was entered into the regression equation and the percent plot-derived sediment in the runoff was calculated.

Ninety-five percent prediction intervals were calculated to assess the uncertainty associated with the predictions made using the regression (Chatfield 1993). The prediction intervals were calculated using the following equation (n=35):

$$\text{Regression prediction} \pm (t)*(s^2 * \sqrt{(1+1/n)} \qquad (1)$$

The 95% confidence intervals for the mean predicted plot-derived sediment in each month were calculated using the following formula (n=8 for each month).

$$\text{Mean plot-derived sediment} \pm (t)* \sqrt{(s / n)} \qquad (2)$$

where: t = t statistic, s = standard deviation, and n = sample size.

The sediment trapping efficiency of the vegetated channels was calculated using the following equation after Coyne et al. 1995. The sediment in the runoff that originated from within the plot can be taken into account by using the following adjusted sediment trapping efficiency equation:

$$\text{Sediment trapping efficiency} = (S_A - S_R) / S_A \qquad (3)$$

$$\text{Adjusted sediment trapping efficiency} = [S_A - \{S_R \text{ x } (1\text{-PPDS})\}] / S_A \qquad (4)$$

where: S_A = mass of sediment applied, S_R = mass of sediment in runoff, and PPDS = percent plot derived sediment.

The regression equation, prediction intervals, confidence intervals, and sediment trapping efficiencies were calculated using Microsoft Excel (Microsoft, Redmond, WA). Particle size distribution and C content of the introduced, plot, and runoff sediment were compared using t-tests calculated in Microsoft Excel (Microsoft).

Results and Discussion

The sediment collected in March (7.5% C) did not differ in C content from the sediment collected in September (8.4% C) (t-test, DF=14, p=0.11). Research suggests that soils change in C content due to management practices such as tillage and crop rotation. However, measurable changes in soil C content are not likely seasonal and occur on the scale of years or decades (Sherrod et al. 2005; Follett et al. 2009). No published research was located addressing the seasonal changes of sediment C content. That could be an area of future research because sediment in overland flow is a substantial means by which labile C is redistributed throughout a watershed (Jacinthe et al. 2004) and a means by which changes could occur over time scales of weeks or even days.

The equation for estimating percent plot derived sediment C content as a function of percent plot-derived sediment (see Fig. 2) is:

$$C_R = (0.06 \times PPDS) + 0.64 \tag{5}$$

where: C_R = runoff sediment C content (%) and PPDS = percent plot derived sediment (0 or 100%).

The sediment C content in the runoff collected in April, June and August was entered into the equation as C_R, and the equation was solved for PPDS to determine the amount of plot-derived sediment in the runoff.

It was assumed that the relationship between sediment C content and percent plot-derived sediment was linear. This follows multiple studies in which linear mixing models were used in watershed-scale sediment fingerprinting studies (Peart and Walling 1986; Walling et al. 1993; Russell et al. 2001). The assumption of linearity seems particularly defensible in this study because water and sediment from a runoff event equivalent to that caused by a 15 minute storm with a 5-year return period from an area 20 times as large as each plot was applied for each trial. That is, variability that might exist in an area 20 times the size of the plot area was eliminated using this technique. It has also been observed that sediment export rate from a watershed is linearly related to C export (Jacinthe et al. 2004). Jacinthe et al. (2004) suggest that low intensity storms sort C fractions more than do high intensity storms; the five year return storm used in this study does not fall into the low intensity storm category.

Due to random selection of experimental units to be used, there were only two treatments that could be compared. There was no statistical difference (t-test, p=0.18, DF=4) between the mean percent plot-derived sediment for the corn and smooth bromegrass plots (Table 1). Over the three runs of the experiment, when soil material mixed with water was introduced to the plots, 20.5% (mean upper level CI=22.9, mean lower level CI=18.0) of the sediment in the runoff exiting the plot was plot-derived (Table 2). This indicates that with 95% certainty, plots contributed between 18.0 and 22.9% of the sediment collected in the runoff. It has been suggested that vegetative filter strips can be both sources and sinks of sediment to runoff that enters and flows through waterways (Dillaha and Inamdar 1996). However, prior to this research the relative amount of sediment that a vegetative structure similar to a vegetative filter strips supplies to runoff has not been quantified under experimental conditions.

The mean particle size distribution (PSD) of the sediment exiting the plot when only water was introduced onto the plot was 34% sand, 42% silt, and 24% clay (Table 3). The mean PSD of the applied sediment was 8% sand, 55% silt, and 37% clay. The mean PSD of the sediment collected in the runoff during the three months was 2% sand, 58% silt, and 40% clay. The PSD of the applied sediment and runoff sediment was not statistically different when analyzed using a t-test (sand $p=0.11$, silt $p=0.69$, clay $p=0.69$). This suggests that substantial particle sorting did not occur during water and soil material mixture flow through the plot and the particles leaving the plot were primarily the same size as those that were introduced onto the plot with water. In other words, water with an existing sediment load flowing into these plots did not seem to scour or remove substantial sediment from the soil surface. However, the sediment collected at the outlet had a C content statistically different from that of the introduced soil material and plot sediment (t-tests, DF = 28, $p<0.001$). Basing mixing and sorting conclusions only on textural change data would lead one to conclude the sediment entering the grass plot had little interaction with soil in the plot. However, C fingerprinting suggests interactions did occur and that, based on both analyses, particles of a given size from the introduced soil material that remained in the plot were replaced with plot particles of similar diameter.

Sediment fingerprinting studies conducted on relatively large-scale watersheds have produced varying results with regard to the source of sediment exiting the watershed. Some studies have identified cropland as the largest source and stream banks as the smallest source of sediment exiting the watershed (Peart and Walling 1986). However, others suggest that stream banks are the primary source of sediment to the river or stream waterways (Kronvang et al. 1997). While this study was much smaller in area and focused on grass areas not containing perennial flowing water, we came to similar conclusions as that of Peart and Walling (1986): the applied soil material (simulated from cropland) was a much greater source of sediment in the runoff than was soil material from the area experiencing channelized flow (perennial grass area in this study). In the process of soil erosion by water, rain drop impact is the primary agent of detachment of soil particles where overland flow is not dominating. In areas of concentrated overland flow greater than 2 mm deep, such as in vegetated channels, runoff is the primary agent of both detachment and transportation of soil particles (Proffitt and Rose 1991). Additionally, the vegetation in the vegetated channel would intercept the energy from falling raindrops, basically eliminating raindrop impact as a significant contributor to the detachment process. While this study only dealt with runoff, not rainfall, similar results would be expected if rainfall were occurring.

Methods for identifying the sources of sediment on small-plot runoff experiments, such as those in this study, have not previously been published. However, sediment source identification studies have been widely published from watershed-scale studies (watersheds >2 hectares) (Peart and Walling 1986; Walling et al. 1999; Russell et al. 2001). There are several differences between this study and watershed-scale studies that suggest the proposed approach to sediment fingerprinting is relatively simple and more accurate in small-plot runoff experiments (Walling et al. 1993). In small-plot experiments, sediment can be directly collected. Watershed-scale experiments often analyze only the <63 micron fraction, assuming that it is the only fraction of soil leaving a watershed in a stream or watercourse (Walling et al. 1993, 1999; Russell et al. 2001). The chemical and physical properties of soil and the sediment eroded from a watershed can vary widely (Young 1980; Farenhorst and Bryan 1995). Small-plot runoff experiments, such as that described here, offer better control of potential sediment sources within watershed locations—there are only two sediment sources, the introduced sediment and sediment originating from the study area. This cannot be said for watershed-scale studies as there can be many sources of sediment that can vary widely in chemical composition (forests, grassland, cropland, filter strips, stream banks, and stream channels).

Under the conditions used in this experiment, the vegetated channels were highly efficient at trapping applied sediment (Table 4). On average, the vegetated channels trapped 92% of the sediment applied to them. Sediment trapping efficiencies typically range from 75% to over 98% when using methods similar to those used in this study (Coyne et al. 1995). The high sediment trapping efficiencies observed in this study are most likely due to the fact that this runoff simulated a 15 minute, 5 year return period storm. If the storm were of greater duration or more intense, the sediment trapping efficiency of vegetated channels would likely decrease. Because the vegetated channels were so efficient at trapping sediment, the adjusted sediment trapping efficiency was similar to the standard sediment trapping efficiency calculations (Table 4). Percent plot derived sediment would be more influential in storms with greater intensities. Not only would these storms most likely result in lower sediment trapping efficiencies, but the runoff would have more power to detach plot sediment.

The "watershed" in this study differs from watersheds in which previous studies were conducted. However, it seems advantageous to use the method presented in this paper in conjunction with large, watershed-scale sediment fingerprinting studies to greatly enhance our understanding of soil movement dynamics. Larger watershed scale fingerprinting could be used to identify problem areas within a watershed. And, once the problem areas within a watershed are identified, experiments at the problem area, using the method proposed in this study, could be a powerful tool to determine sediment movement dynamics with a variety of management practices.

Conclusions

Sediment fingerprinting has been conducted in large, watershed scale studies to identify the source of sediment being exported from watersheds. In this study we have used similar, but not identical, methods to determine the amount of sediment that is derived from the plot bed in small-plot runoff experiments. When runoff mixed with soil was introduced to small plots, we determined that on average 20.5% of the sediment in the runoff from the plot was derived from the plot bed. The plots in this study were relatively efficient in trapping sediment so correcting the sediment trapping efficiency did not have a large impact on the actual sediment trapping efficiency of the plots. However, in less efficient systems, accounting for the sediment derived from within the plot could have a large impact on the true sediment trapping efficiency of small plots during small plot runoff experiments.

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Table 1.

A description of each plot used in the project including: grass species, biomass removal, stem densities, and percent plot derived sediment by month.

Plot	Grass Species	Biomass Removal	Target Species (Stems / m^{-2})	Non-Target Species (Stems / m^{-2})	April Percent PDS	June Percent PDS	August Percent PDS	Mean Monthly Percent PDS
13	Corn	Removed	6	0	na	25.0	18.9	22.0
18	Smooth bromegrass	Not removed	860	0	20.4	23.0	18.4	20.6
22	Corn	Not removed	6	0	16.7	19.8	16.9	17.8
24	Smooth bromegrass	Removed	750	0	16.6	19.3	29.4	21.8
28	Switchgrass	Not removed	375	175	19.3	29.4	20.1	22.9
34	Switchgrass	Not removed	340	340	29.4	20.1	23.7	24.4
35	Corn	Not removed	6	0	20.1	16.7	19.1	18.6
37	Smooth bromegrass	Not removed	775	0	23.7	27.8	na	25.8

Abbreviations: PDS, plot derived sediment; na, data not available

Table 2.

Runoff sediment C content and percent plot derived sediment by month with confidence limits (C.L) and prediction intervals (P.I.)

Month	Mean Runoff Sediment C content (%)	Mean Percent Plot Derived Sediment (n=8 for each month)	Upper 95% C.L.	Lower 95% C.L.	Upper 95% P.I	Lower 95% P.I.
		-------------------Percent Plot Derived Sediment----------------------				
April	1.3	20.9 (4.5)[£]	24.5	17.2	36.2	5.6
June	1.2	22.4 (3.6)	25.3	19.4	37.7	7.1
August	1.4	18.2 (0.8)	18.9	17.5	33.5	2.9

[£]Number in parentheses is the standard deviation of the mean

Table 3.

Sediment particle size distribution of a composite sample from each month.

Sample		Sand	Silt	Clay
		----------------------Percent----------------------		
100% Plot-Derived Sediment				
	March	28	50	22
	September	40	35	25
Applied Soil Material				
	April	6	55	39
	June	13	62	25
	August	5	48	47
Runoff Sediment				
	April	2	53	45
	June	4	51	45
	August	1	69	30

Table 4.

Mean sediment trapping efficiency and adjusted mean sediment trapping efficiencies for each month the experiment was conducted.

Month	Mean Sediment Trapping Efficiency	Adjusted Mean Sediment Trapping Efficiency	Mean Difference
	------------------------------------Percent------------------------------------		
April	93	95	+2
June	90	92	+2
August	94	95	+1

Figure 1.

Cross section (A) and aerial view (B) of the experimental units and the position of the application mechanism with respect to the plot

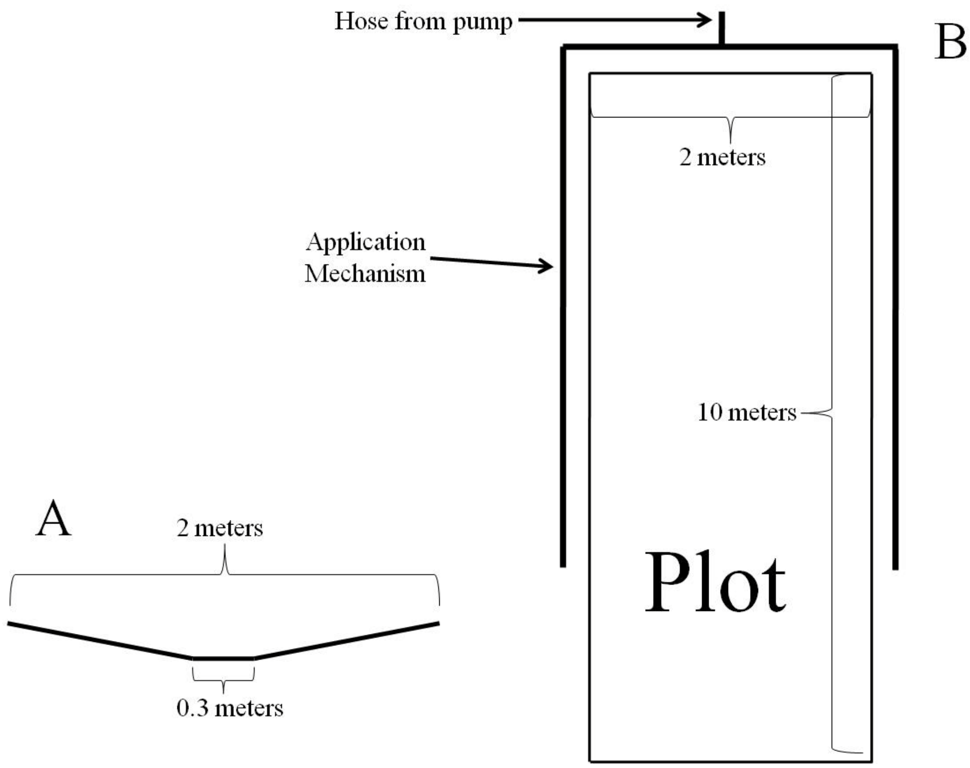
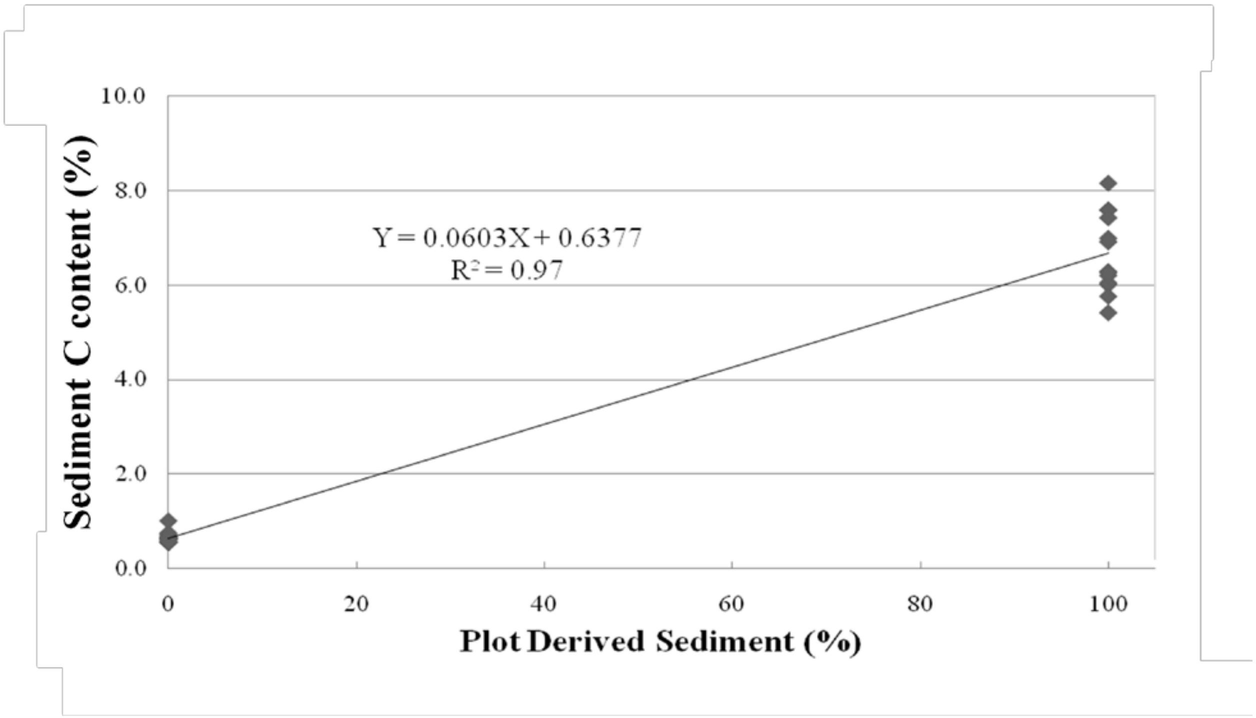


Figure 2.

The relationship between sediment C content and percent plot-derived sediment (n=35).



CHAPTER 4

GENERAL CONCLUSIONS

General Summary

The conversion of plant biomass to fuel may offer new market opportunities to farmers. For example, perennial grasses growing in environmentally sensitive areas or in Conservation Reserve Program (CRP) lands could be harvested and sold in the biofuel market place. In fact, there are several conservation practices with land planted to perennial grass that could serve as potential sources of biomass. These include vegetated riparian areas, vegetated filter strips, grass waterways or vegetated channels, and grass-based field borders.

The overall goal of my dissertation was to address the impact of biomass removal on sediment transport through vegetated channels and to develop methodology to identify the sources of moving sediment in plot studies. Two conservation practices that experience channelized flow are grassed waterways and vegetated filter strips. Grassed waterways are designed to convey channeled runoff, while vegetated filter strips are designed to intercept sheet runoff, but channels often form in filter strips.

The objective of the study in Chapter 2 was to determine the effects of biomass removal from vegetated channels planted to different grass species on runoff and sediment export during the establishment phase of the grasses. In June of 2006, twenty-four channels were created that measured 2m wide x 10 m long with 12.7% sideslopes. The grasses (smooth bromegrass, *Bromus inermis*; switchgrass, *Panicum virgatum*; big bluestem, *Andropogdon gerrardi*) were planted within a week of the channel creation, and the channels to be planted to corn were left fallow in 2006 and planted to corn in 36 inch rows in 2007 and 2008.

This study simulated runoff events from a 15 minute storm with a 5 year return interval and a contributing area 20 times larger than the channel. A 787 L load of water mixed with 7 kg of dried and 8 mm sieved soil was constantly stirred and applied to the head and sides of each vegetated channel in June, August, and October of 2007 and in April, June, and August of 2008 at a rate of 80 L min^{-1}. The runoff application device was made of 3.2 cm diameter polyvinyl chloride pipe with dimensions of 6.5 m long and 2 m wide and 0.6 cm diameter holes drilled every 0.15 m. Aboveground biomass was mowed on all vegetated channels in October and half of the vegetated channels had all of the mowed biomass removed from them. A split-plot design with 3 replications was used with grass species (n=4) being the whole plot treatment and biomass removal (n=2) being the split treatment. Biomass removal increased runoff and sediment export by an average of 15% over the two years of the study. The vegetated channels planted to perennial C4 grasses (big bluestem and switchgrass) were most effective at reducing runoff and sediment export, while the vegetated channels planted to corn were consistently the least effective at reducing runoff and sediment export during this study.

In Chapter 3's study, the objective was to apply watershed-scale sediment fingerprinting techniques to small-plot runoff experiments. This allowed the sediment exiting the plot to be partitioned between the sediment that entered the plot with run-on water and sediment that originated from the plot. Watershed-scale studies often use several sediment chemical parameters (total C, total N, ^{137}Cs, ^{210}Pb, conductivity, magnetic properties, total P, and Mn) to fingerprint the sediment exiting a watershed. In this study, the total C content of the different sediment sources was used to calculate a linear equation that estimated the amount of plot-derived sediment in the runoff. Sediment particle size distribution was measured and used to validate the calculations from the equation. This is advantageous because total C and texture analyses are simpler and less expensive than are the analyses conducted in watershed-scale fingerprinting experiments.

Conservation practices used to trap sediment are often developed and tested on small plots. Using the runoff application methods described previously, a water-only load with no soil material mixed in was applied to eight randomly selected vegetated channels. The subsequent runoff from the vegetated channel was collected until the volume of the sample reached 10 L. The sediment in this sample represented sediment that was 100% derived from the vegetated channel. A 787 L load of water with 7 kg of sediment mixed in (load) was applied to the same 8 randomly selected vegetated channels in April, June, and August of 2008. The load was sampled as it was applied to each vegetated channel and as it ran off each vegetated channel. The sediment collected from the load as it was applied to each vegetated channel represents sediment that was 0% derived from the vegetated channel. The sediment collected from the water that ran off of the vegetated channel represents a sample that is a mix of plot and applied sediment.

A linear equation was calculated with sediment C content as a function of percent vegetated channel derived (PVCD) sediment (0 or 100%). The C content of the sediment in the runoff was entered into the linear equation and PVCD sediment was calculated. The small-plot experiments in Chapter 2 measured the amount of sediment leaving the plot as a fraction of the sediment applied, but did not differentiate that sediment between applied sediment and plot-derived sediment. When using this simplified method to segregate runoff sediment source, it was determined that, on average, 20.5% of the sediment in the runoff was derived from the vegetated channel.

Suggestions for Future Research

The results found through this doctoral research have generated some new questions for study. The study in Chapter 2 evaluated the effects of biomass removal and grass species on runoff and sediment export from vegetated channels during pulse-flow runoff events. Over the duration of the experiment, the grass stands were still in the establishment phase, which is dominated by grasses other than the seeded species. It is important to determine the results once the grasses are fully established. If the runoff events simulated in the experiment were longer or more intense, the effects of biomass removal and grass species could be more pronounced than what was observed in this study. It would be useful to know how or if runoff events of different depths and duration have similar results as those in this study. It seems important to utilize fingerprinting methods to determine the source of sediment for the scenarios described above. This would allow determination of channel stability for the different species and give evidence of vegetated channel stability against gulley formation—something of concern when these channels are managed for multiple purposes.

The general procedures used in Chapter 2 are often used to develop best management strategies for conservation practices. While the net trapping of sediment in these practices has been determined, differentiating sediment sources (sediment fingerprinting) in the runoff has not been attempted. The study in Chapter 3 developed and tested a method to do so. Future research could be done to validate, refine, and make improvements to the method. Future research can now use this method to compare different treatments and develop best management strategies that could minimize sediment loss from within conservation practices.